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INVESTIGATION OF FLAME VELOCITIES AT LOW PRESSURES

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SUMMARY

The purpose of this study is to investigate flame velocities of mixtures of oxygen and various fuel gases at low pressures. Acetylene and propane fuels were used, and flame velocities were measured by means of flat disc flames and by means of the geometry of cone-shaped flames. Flame front area was measured from the profile defined by the onset of luminosity. The pressure range from three to one hundred mm. of mercury was covered by using two burner inlet ducts of different diameters, 2.37 and 1.25 inches respectively. The equipment and characteristics of the low pressure flame limited the data in this range, so that restricted quantitative results were obtained in regard to the variation of flame velocities with pressure.

Qualitatively, very definite variations were noted. There is a marked decrease of flame velocity with decreasing pressures in the regime below forty mm. of mercury. The variation in flame speed for the same pressure increments becomes greater as the pressure decreases. This is attributed to the rapid increase of the quenching effect from the inlet duct rim at these low pressures and low flow velocities. It is also found that flame velocities from flat flames are consistently lower than those obtained through the geometry of the cone flames. Similarly, flame velocities measured with the smaller inlet duct are consistently lower than those measured with the larger duct for the same measuring criteria. Both these variations appear to be explained by the large quenching effect encountered.

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PART I

INTRODUCTION

The purpose of this study was to investigate flame velocities of mixtures of oxygen and various fuel gases at low pressures. It was originally planned to compile experimental data for several fuel gases: CO, NO, C_2H_2, CH_4, H_2, and C_3H_8. However, time limited the schedule to the extent that only C_2H_2 and C_3H_8 have been very thoroughly investigated. Earlier researchers have suggested variation of flame velocity with pressure according to different laws. Tanford and Pease (Ref. 1) proposed a fourth root of pressure dependence, whereas Gaydon and Wolfard (Ref. 2) and Gilbert (Ref. 3) conclude that flame speed appears to be independent of pressure.

It was further hoped to derive some conclusions concerning the ignition boundary. Gaydon and Wolfard suggest that exothermic reaction corresponds to the onset of luminosity. This criterion is used throughout this work that it may be perhaps verified by the results.

Two distinct methods of measuring flame speed have been used here: the usual procedure based on the geometry of cone-shaped flames, and a simpler method based on relatively or completely flat flames. The latter has been proposed by Gilbert (Ref. 3) under the logic that the effect of displacement of ignition boundaries into the dark zone is minimized and the average jet velocity can be used with more certainty as an indication of average flame speed. Here it is anticipated that the phenomenon of quenching, more pronounced at low pressures, may effect the results considerably, because the flat flame is in closer proximity to the rim of the duct than is a conical flame over all sections of the flame zone.

PART II

EQUIPMENT

The combustion chamber, pumping system, and flow system used in this work have been very completely described by Gilbert (Ref. 3). Essentially, the apparatus consists of a double-windowed combustion chamber, 24 inch inside diameter and 60 inch height; a vacuum system utilizing a Kinney model DVD 1414818 mechanical vacuum pump and an acoustic filter; and a two-stage pressure regulated flow system with Fisher-Porter C-clamp calibrated Flowrators for measuring the volume flow.

The valves which control the flow are long taper needle valves downstream from the Flowrator selector valves. The upstream pressure is constant at 40 psia. The pressure downstream of the needle valves is of the order of the vacuum pressure in the chamber. The pressure ratio is therefore always greater than critical; the mass flow then depends only on the upstream conditions. Moreover, there is an inverse proportion between the velocity at the burner port and the chamber pressure since the mass flow is constant. Flow control by means of critical pressure drop contributes to the extremely steady flames observed.

The pressure in the combustion chamber is controlled by means of a sensitive needle valve in the bleed system. The valve allows a constant leak of atmospheric air into the acoustic filter through a long length of 3/4 inch copper tubing. With the bleed air entering far downstream and close to the pump, no appreciable dilution can occur in the exhaust gas atmosphere surrounding the flame. The

pressure is easily controlled within the response sensitivity of the Wallace-Tiernan absolute pressure gauges which have an absolute accuracy better than .03 mm. of mercury, with some adjustment.

From the control valves, the gases flow through a mixing chamber and thence into the circular inlet duct. At the entrance of this duct is located a honey-comb filter made up of a bundle of three inch lengths of 1/8 inch thin-walled stainless steel tubing. This serves to produce a uniform velocity and suppress disturbances produced in the mixing chamber. The burner duct length is then sufficient to allow the building up of the parabolic velocity profile characteristic of laminar pipe flow by the time the duct exit is reached. The exit is contained in an annular water-cooled chamber and is flush with its flat upper surface. This prevents excessive heating of the exit and also assures a constant temperature surface where quenching effects are considered.

Two different size inlet ducts are used in order to cover a wider pressure range, one 2.37 inches inside diameter and the second 1.25 inches inside diameter. The details of the two are identical except for diameter.

The only added apparatus, essential to this work, is an optical system (Fig. 1) for securing an image of the flame. This system consists of a double-convex lens, 4 inches in diameter and 40 inch focal length, mounted outside one chamber window, and a pedestal mounted glass plate which, when covered with a piece of onion-skin paper, serves as a screen upon which the inverted image appears. The system is adjusted so that the image appears full

scale by placing the lens at distance $\frac{1}{2}$ f (focal length) and the screen at distance f from the flame. Thus a scale flame profile may be traced in a few seconds, a more simple and handy arrangement than photography could offer for the large number of flame profiles required, even in this limited work, approximately three hundred.

PART III

EXPERIMENTAL PROCEDURE

Work was started with the 2.37 inch burner duct to investigate the extremely low pressure flames. Acetylene-oxygen mixtures could be burned at the lowest obtainable pressures, about one mm. Hg, but the flames were too diffuse to permit any determination of flame speed with present knowledge. At three mm Hg. the flames became sufficiently defined to permit estimating an ignition boundary. The criterion, as noted earlier, was taken as the onset of luminosity. Since the flames were all three-dimensional, the location of an inner cone could not be precisely determined, particularly at the lowest pressures, because of the considerable thickness of the flames. For example, the bright blue-white zone of the acetylene flame at 3 mm. is on the order of 3/8 of an inch thick with shading off into a blue and then violet outer zone of similar thickness. (Figs. 2 and 3 show typical flames at 6 mm. and higher pressures.) The scatter of points at 3 and 4 mm. (Fig. 5), representing data based on cone profiles, indicates this difficulty of determining the ignition boundary when the reaction zone is so thick. As pressure increases, flame thickness decreases and the inner cone can be traced with increasing certainty. For acetylene-oxygen mixtures acceptable data is obtained at 5 mm. and higher pressures. The lower brilliance of propane oxygen flames made it impossible to trace a flame front with any accuracy for the cone-shaped flames at mixtures much less than stoichiometric and pressures less than 10 mm. This explains the lack of lean mixture data in Fig. 7.

Because of their geometry, flat flames can be definitely obtained and controlled at lower pressures than cone flames. Very nice data is secured for acetylene-oxygen flat flames at 3 and 4 mm. For example, a stoichiometric flat flame burning with the 2.37 inch duct at 3 mm is obtained with a total volume flow of 4200 cc/min. Maintaining the mixture ratio, a change of 70 cc/min volume flow in either direction will cause the flame to become convex or to dip into the duct. In other words, the measurement itself is accurate and reproducible within $2^{o}/o$. Many check points were taken to establish this figure.

Pressure was the fixed parameter in taking data; mixture ratio and total volume flow were varied. At the lower pressures the pumping system was working near capacity and pressure control was consequently very sluggish. Therefore, it was felt adequate to keep pressure within 0.05 mm of that chosen.

The outline geometry of low pressure flames is not nearly so definite to work with as that of atmospheric bunsen flames. The cones are rarely sharply pointed and the base diameter does not often equal the duct diameter. At such low pressures and resulting low volume flows, the outward deflection of the flow lines is a more general phenomena increasing the overall lateral dimensions, and not just the diameter of the base as in the bunsen flame at atmospheric pressure. Consequently, the calculation of the flame front area is modified somewhat from the conventional procedures. The traced profile is approximated by the appropriate geometrical profile. For the general class of conical flames, various profiles

were fitted in search of the closest approximation: right circular cone, paraboloid, spherical surface, truncated cone plus spherical surface, and truncated cone plus paraboloid. It was found that the various approximations produced flame front areas which varied less than 3°/o from the area as calculated from the right circular cone. Hence, for ease of calculations and consistent practice, the right circular cone approximation was adopted.

The following simple development provides the basis for the reduction of experimental data.

Recorded data: pressure . . . . mm of Hg
fuel gas volume flow. . . . . std cc/min
oxygen volume flow . . . . . std cc/min
profile of flame front

Flow conditions inside the inlet duct are determined from the metered flow, which is converted in the calibration curves to std cc/min. Temperature is assumed constant since the flame velocity is based on the cold flow.

p_1 = 760 mm of Hg

V_1 = Total volume flow metered

p_2 = Recorded chamber pressure, mm of Hg

V_2 = Total volume flow at chamber pressure

u_2 = Flame velocity

A_2 = Flame front area

$= \pi r\,(r^2+h^2)^{\frac{1}{2}}$ for cones

$= \pi r^2$ for flat flames

The Continuity Equation becomes:

$$p_1V_1 = p_2V_2$$

$$V_2 = V_1 \times 760/p_2$$

$$V_2 = u_2A_2$$

$$u_2 = V_1/A_2 \times 760/p_2 \text{ (cm/min)} = .4152\ V_1/A_2p_2 \text{ (fps)}$$

$$\text{Mixture Ratio} = f = \frac{\text{Volume flow of fuel gas}}{\text{Volume flow of oxygen}}$$

PART IV

DISCUSSION OF RESULTS

The experimental data are plotted in terms of flame speed versus mixture ratio for the workable pressures (Cf. Figs. 4 through 11). Immediately obvious is the fact that flames are not obtainable over a wide range of mixture ratio at all pressures. A related phenomenon has been noted by Wolfard (Cf. Ref. 4). The diameter of the burner must be increased proportionately in order to obtain a stable flame as the pressure is decreased. Since only two different size ducts were used in this work, more complete variation of flame speed with mixture ratio was not obtainable. Other limitations encountered were: the tendency of richer flames to diffuse at lower pressures, the very low brilliance of lean propane flames, and the maximum oxygen flow capacity of the system, about 20,000 cc/min.

Qualitatively, there is definite decrease of flame velocity with decreasing pressures in the regime below 40 mm (Cf. Figs. 12 and 13). There is no measurable change above 40 mm according to the data obtained up to 100 mm. Wolfard (Cf. Ref. 4) also notes this trend. For acetylene oxygen flames he indicates the same increase in flame speed which levels off at about 20 mm and remains constant thereafter up to atmospheric pressure.

It is interesting to apply the work of Boys and Corner (Ref. 5) to this apparent invariance of flame velocity above 40 mm. They conclude that if the homogeneous reaction velocity varies as $(\text{pressure})^n$, the mass flame velocity will vary as $(\text{pressure})^{\frac{1}{2}(n+1)}$, giving "p" for a bimolecular reaction. Since density is proportional to

pressure, this means that flame velocity will vary as $pxp^{-1}=p^{o}=1$, or, in other words, not at all. Thus, the acetylene-oxygen and propane-oxygen combustion processes fit into this scheme as bimolecular reactions.

The limiting curves of flame velocity appear to be the same as those found at atmospheric pressure. Extensive experimental data for atmospheric pressure flame velocities had not been located at the time of writing this report. However, comparison can be made with the curve presented by Lewis and von Elbe (Ref. 6 and Fig. 14) for acetylene-oxygen burning velocity. This is a calculated curve, verified by a few points obtained independently from cone dimensions. The shape of the curve is very similar to that obtained in this work, with the peak at a fuel-air ratio of about 0.43. However, velocities are consistently lower, the greatest difference occurring near stoichiometric ratio, 18.5 fps as compared with approximately 22.5 fps found in this study. On the other hand, Wolfard (Cf. Ref. 4) reports a maximum acetylene-oxygen burning speed of about 9 m/sec, or about 29.5 fps. The propane-oxygen data checks very closely with atmospheric data by Damkohler (Ref. 7 and Fig. 15) with the exception that Damkohler shows a peak at a fuel-air ratio of about .17 where this experiment indicated the peak at .15. It is interesting to note that in both cases the maximum flame velocity occurs below stoichiometric mixture ratio.

The variation of flame speed between that obtained from flat flames and that from conical flames is particularly significant.

In each case, flat flame speed is consistently less than cone flame speed (Cf. Figs. 16 and 17). There is also a comparable phenomena apparent in comparison of data obtained with the two different size ducts. Flame speed obtained with the small duct is consistently lower than that obtained with the larger duct for the same pressure and geometric flame criterion, i.e., flat or conical flame, (Cf. Figs. 18 and 19). The data are not sufficient to draw precise quantitative conclusions. The variation of flame speed with flat versus cone flame geometry is on the order of 15°/o for acetylene mixtures below 20 mm, and on the order of 5°/o for propane mixtures below 40 mm. The variation with duct diameter is even more marked. It is on the order of 25°/o for acetylene at 5 mm, but decreases to about 3°/o at 10 mm. For propane the variation is about 20°/o at 10 mm and decreases to practically zero at 20 mm.

A very logical explanation for these variations lies in the phenomennn of quenching. The water-cooled rim of the duct is a sink for heat (and probably also for chain carriers due to adsorption of atoms and free radicals). As the distance from the rim increases, the loss of heat and chain carriers decreases and the burning velocity increases. The velocity will not be independent of gas flow and duct diameter unless these parameters are sufficiently large. At extremely low pressures, the volume flows are low and the duct diameters are not large with respect to "depth of penetration of quenching". This is a quantity used by Lewis and von Elbe (Cf. Ref. 6) as a measure of the depth to which the quenching effect of a single surface extends. We may assume a similar relation for this low pressure experiment, given by the formula

$d_p \alpha S_u^o/g_f$, where S_u^o is the burning velocity at flashback and g_f is the critical boundary velocity gradient for flashback. For a cylindrical duct, $g_f = 4/\pi \times V_f/r^3$, where V_f is the volume flow at flashback. Using values for lean acetylene flat flames starting into the duct, the ratio of d_p's is found to be approximately two for the larger duct over the smaller duct. However, the ratio of duct areas is 3.60. Therefore, the effect of quenching will be roughly twice as great with the small duct as with the large. This accounts for the lower flame speeds measured with the small duct for the same pressure and flame geometry. Similarly, since cone areas are on the order of three times the flat area for the same duct, and are in lesser proximity to the duct rim, the effect of quenching on cone flame speed should be noticeably less, which is the case here. It might also be noted that d_p is inversely proportional to pressure, that is, the effect of quenching will be many times greater at these low pressures than at atmospheric pressure. It would therefore be expected that flat flame speed approaches cone flame speed as the pressure increases. This is clearly seen in these experiments (Cf. Figs. 11 through 14).

PART V

CONCLUSIONS AND RECOMMENDATIONS

It appears obvious that quenching effect is the primary reason for the variation in flame velocity found in this study, particularly since the variation becomes less as pressure rises and has practically ceased at a pressure of 40 mm.

The suggestion of Tanford and Pease (Cf. Ref. 1) that flame speed has a fourth root of pressure dependence is definitely not supported by this work. It has supported the conclusion of Gaydon and Wolfard (Cf. Ref. 2) and of Gilbert (Cf. Ref. 3) that flame speed is independent of pressure, with the qualification that at low pressures, a pressure dependent quenching effect predominates. These results for the combustion processes studied have also been seen to agree with the theoretical work of Boys and Corner (Cf. Ref. 5).

The choice of flame front corresponding to the onset of luminosity has not been well-proved in this study. There remains some discrepancy in the acetylene-oxygen flame velocity as compared with atmospheric data of Lewis and von Elbe. As noted earlier, it is difficult to "see through" a three-dimensional flame to a cross-sectional profile at low pressures where luminous zone thickness is many times greater than it would be at atmospheric pressure. The error entailed would be flame front area on the low side, resulting in flame speed on the high side, which is the direction of the discrepancy.

It is suggested that work of this nature could be profitably pursued at greater length in order to secure more complete quan-

titative data. This would require minor alteration of the equipment used in this experiment. Oxygen flow capacity would have to be increased, as would fuel gas flow capacity if mixtures whose stoichiometric fuel-air ratio is greater than one were to be investigated. A larger selection of interchangeable ducts would be necessary to cover properly the complete range up to atmospheric pressure. It is further recommended that cold flow velocity profile surveys and temperature surveys be made to amplify the causes of flame velocity variation with pressure.

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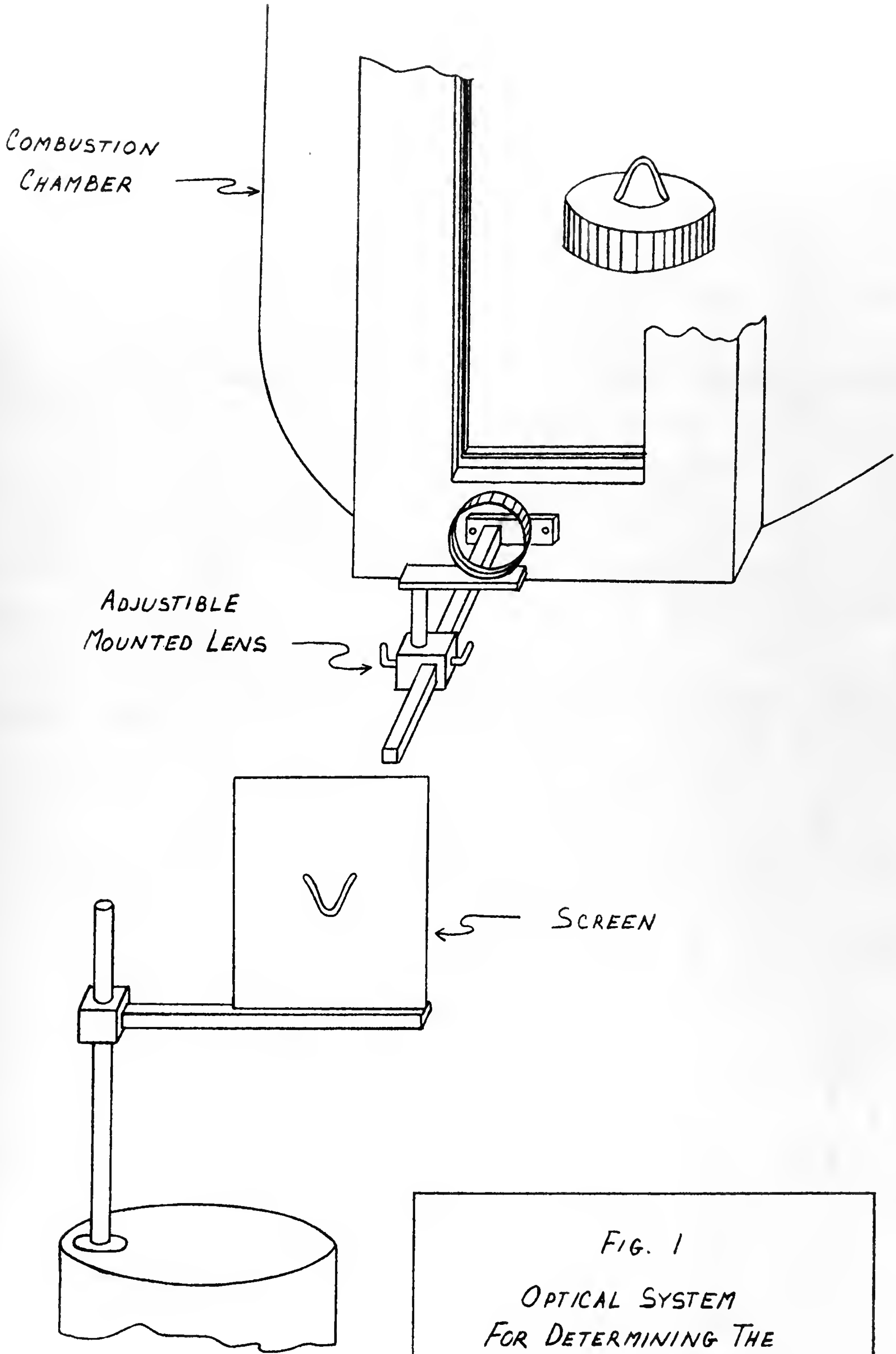

FIG. 1

OPTICAL SYSTEM FOR DETERMINING THE FLAME FRONT PROFILES

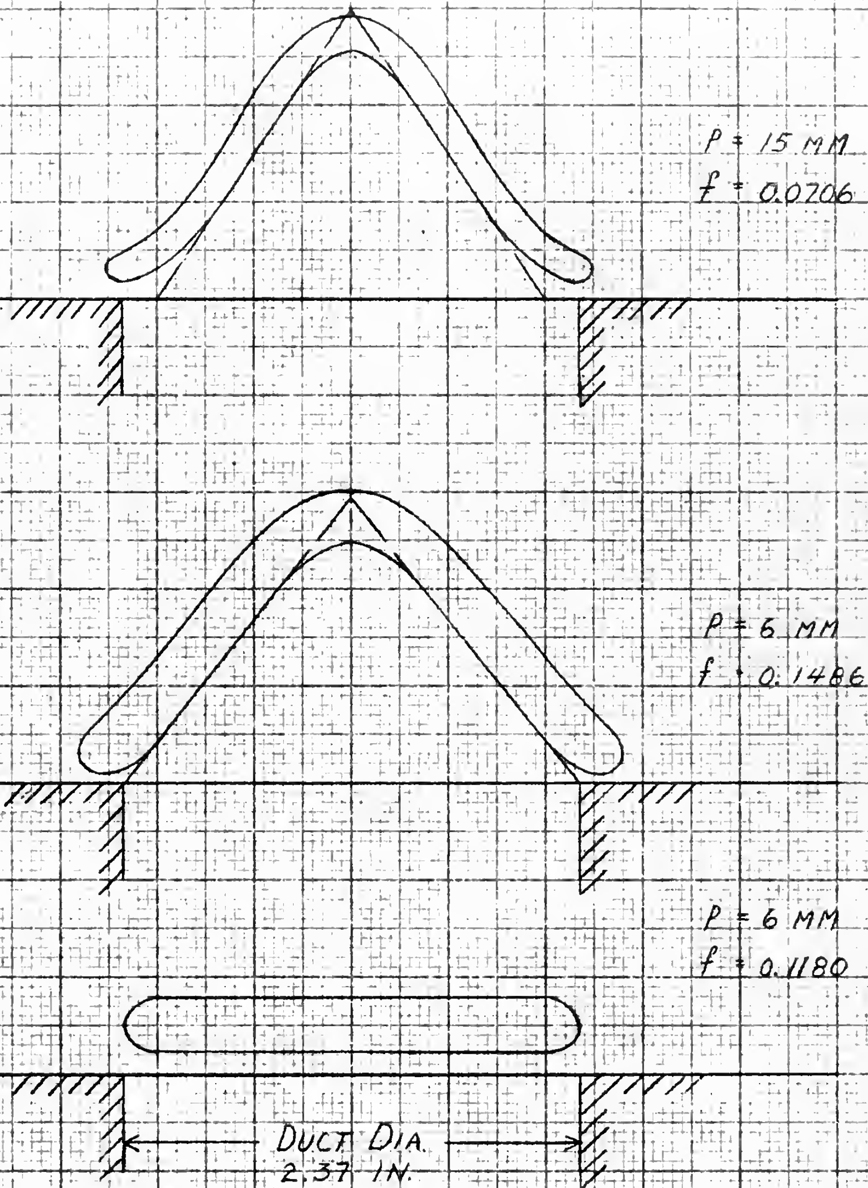

FIG. 2

TYPICAL C_2H_2-O_2 FLAMES
SHOWING THICKNESS
OF BRIGHT BLUE-WHITE ZONE

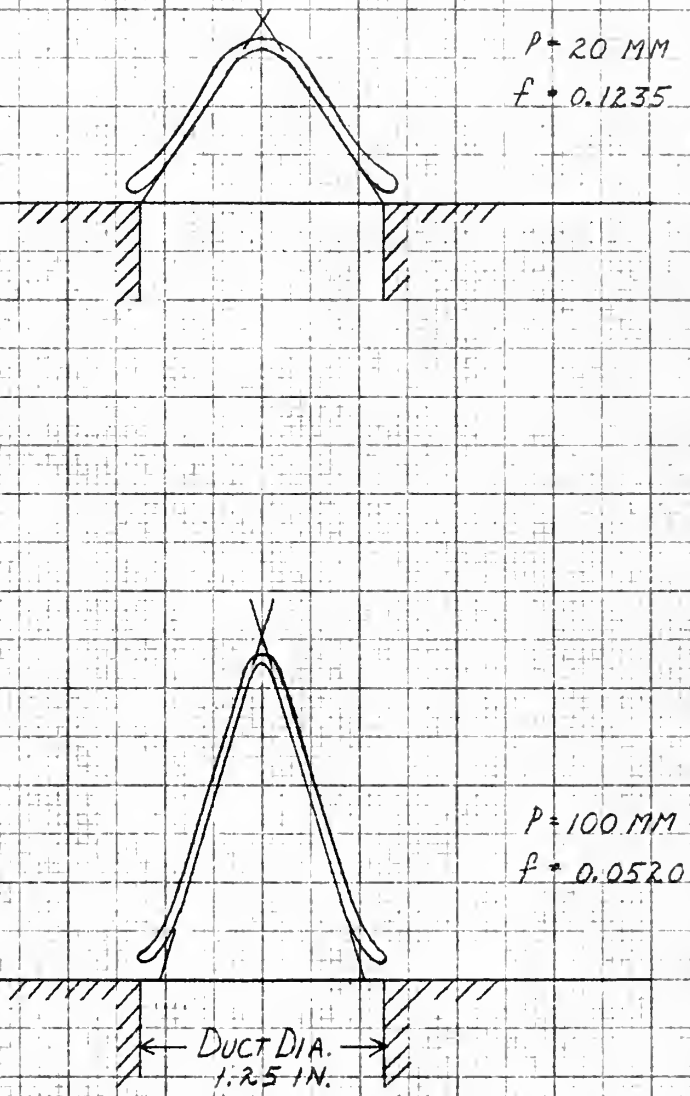

FIG. 3

TYPICAL C_3H_8 - O_2 FLAMES
SHOWING THICKNESS
OF BRIGHT BLUE-WHITE ZONE

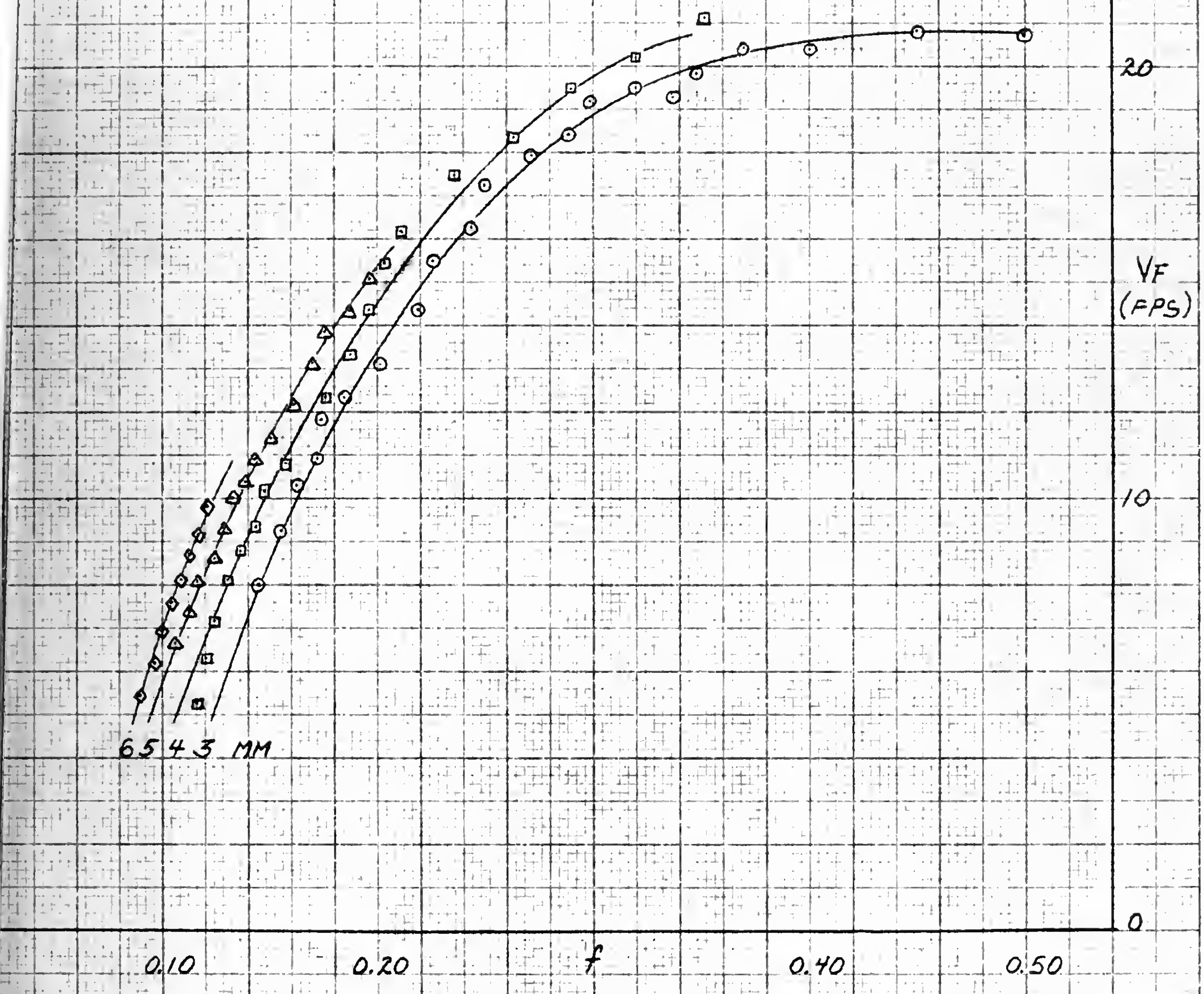

FIG. 4

$C_2H_2-O_2$ FLAME SPEED
DUCT DIA. = 2.37 IN.
FLAT FLAMES

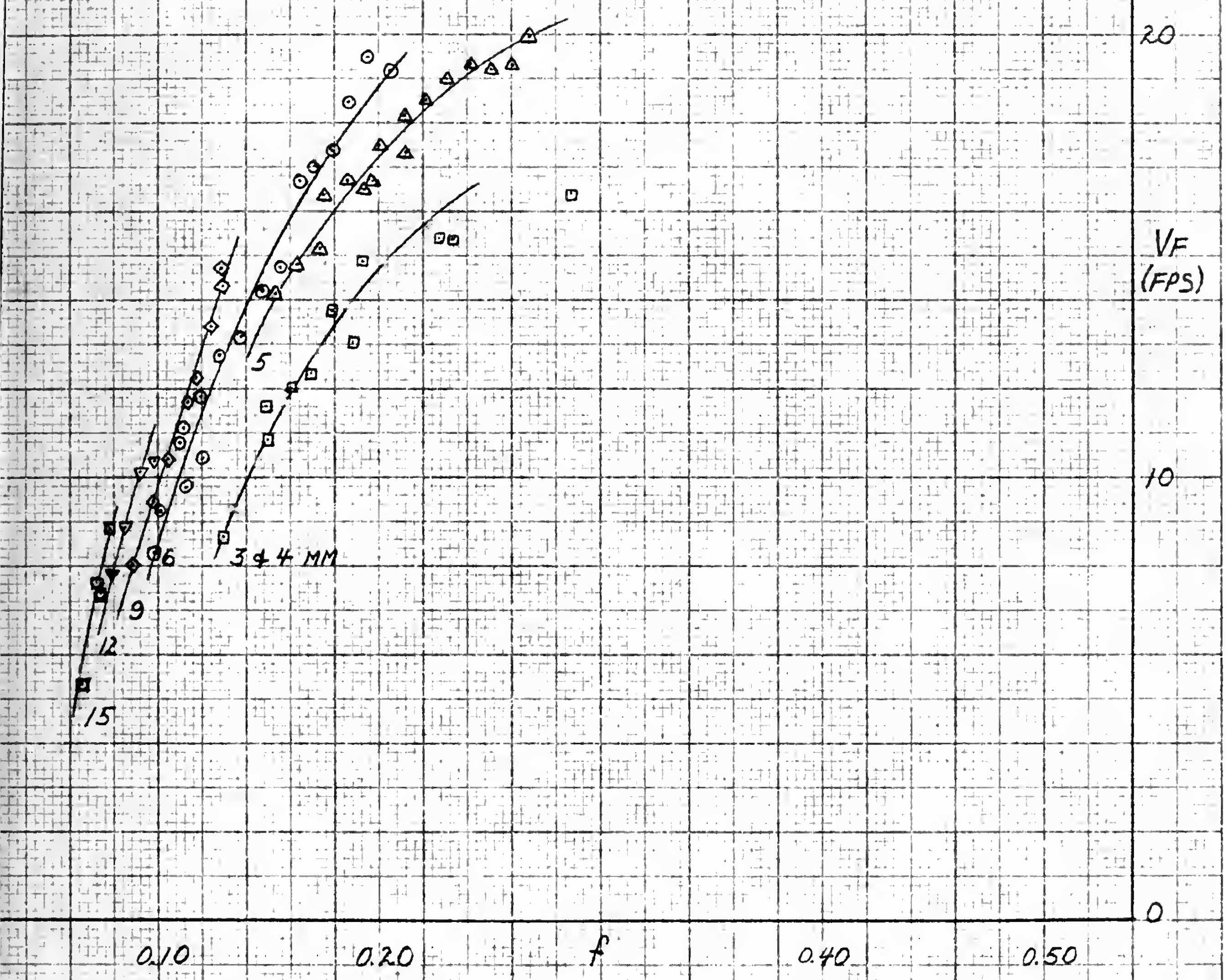

FIG. 5

C_2H_2-O_2 FLAME SPEED

DUCT DIA. = 2.37 IN.

CONE FLAME

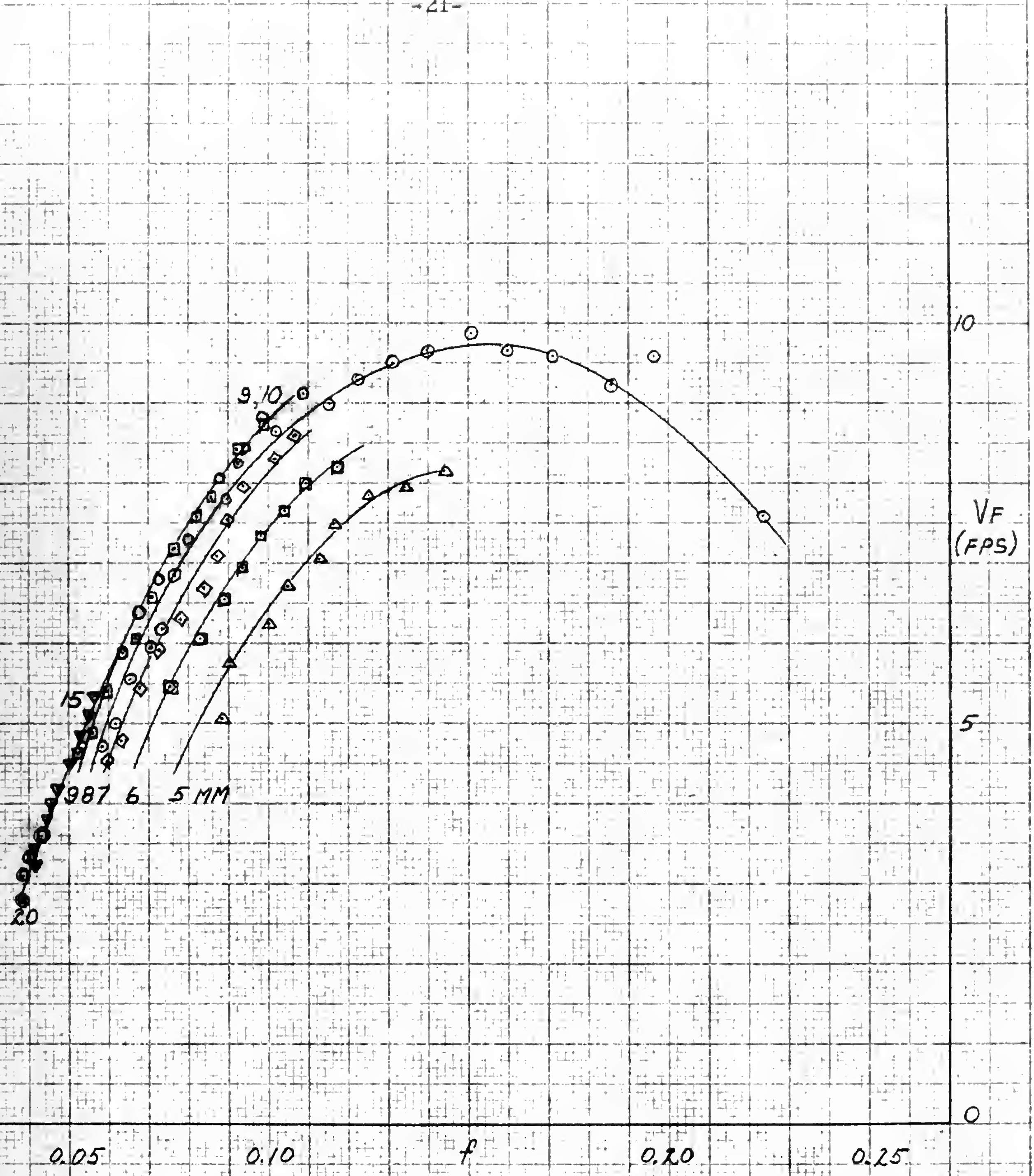

FIG. 6

C_3H_8 - O_2 FLAME SPEED
DUCT DIA. = 2.37 IN.
FLAT FLAME

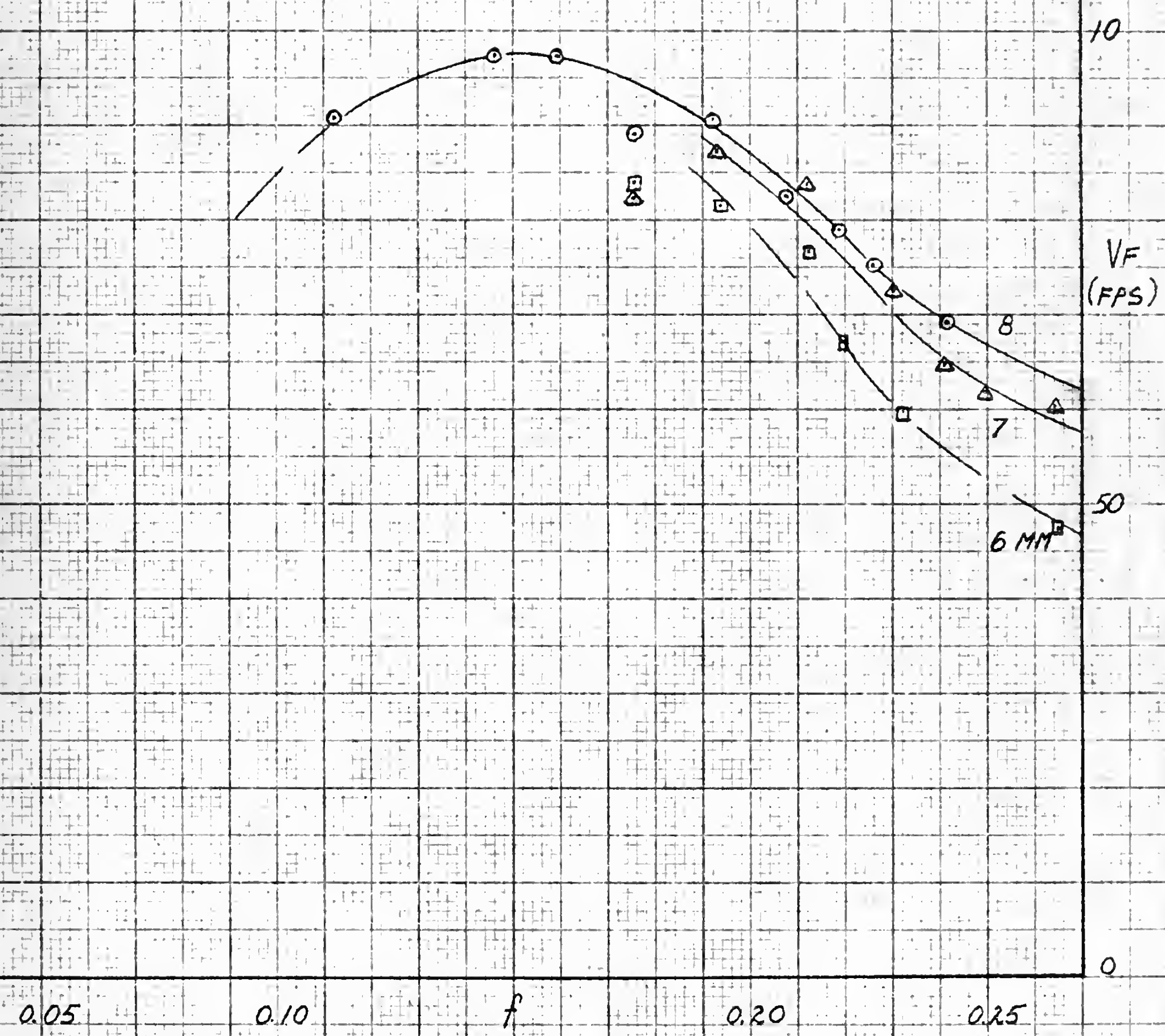

FIG. 7

C_3H_8 - O_2 FLAME SPEED

DUCT DIA = 2.37 IN.

CONE FLAME

FIG. 8

$C_2H_2 - O_2$ FLAME SPEED
DUCT DIA. = 1.25 IN.
FLAT FLAME

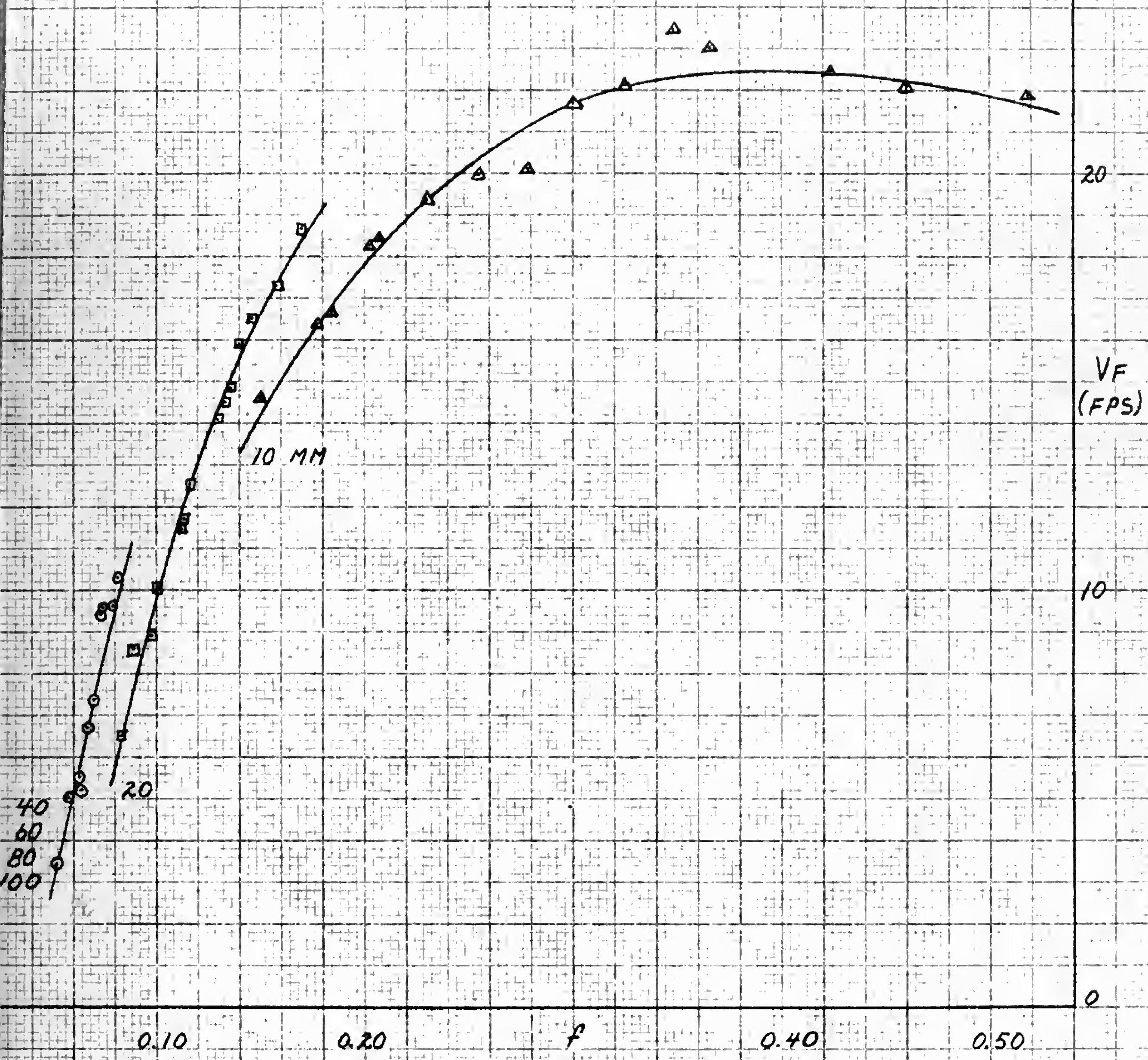

FIG. 9

C_2H_2-O_2 FLAME SPEED
DUCT DIA. = 1.25 IN.
CONE FLAME

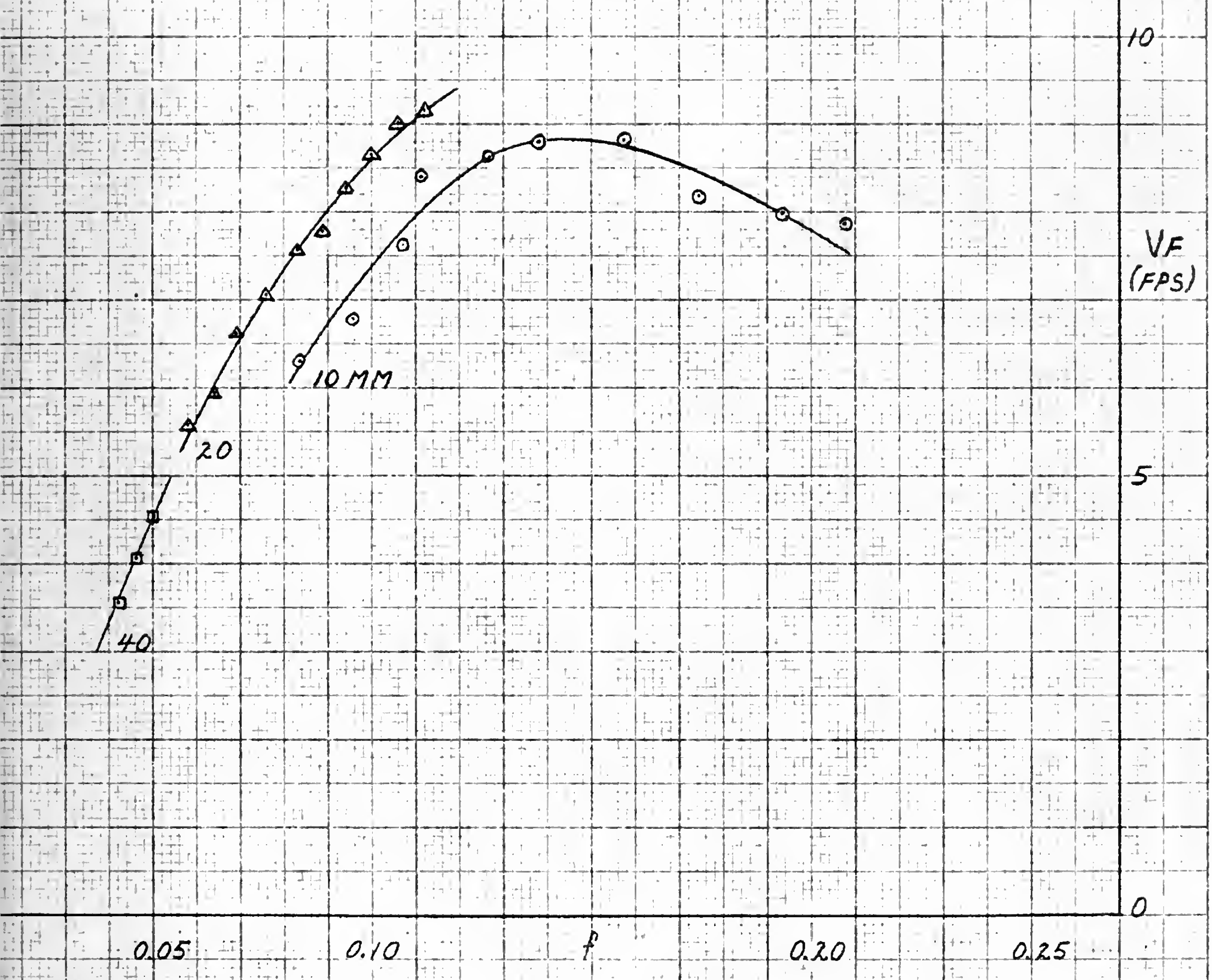

FIG. 10

$C_3H_8-O_2$ FLAME SPEED
DUCT DIA = 1.25 IN.
FLAT FLAME

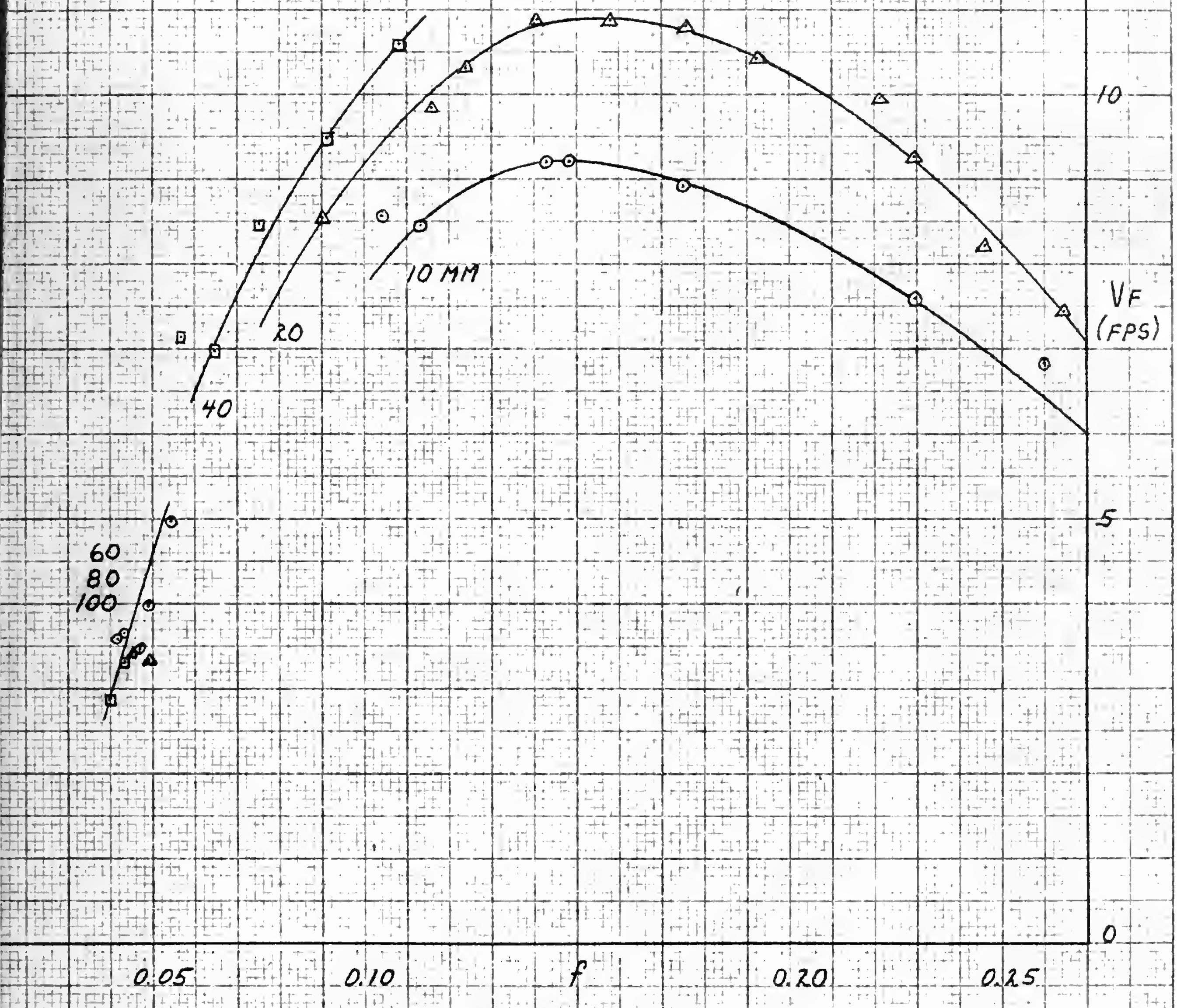

Fig. 11

C_3H_8-O_2 Flame Speed
Duct Dia. = 1.25 in.
Cone Flame

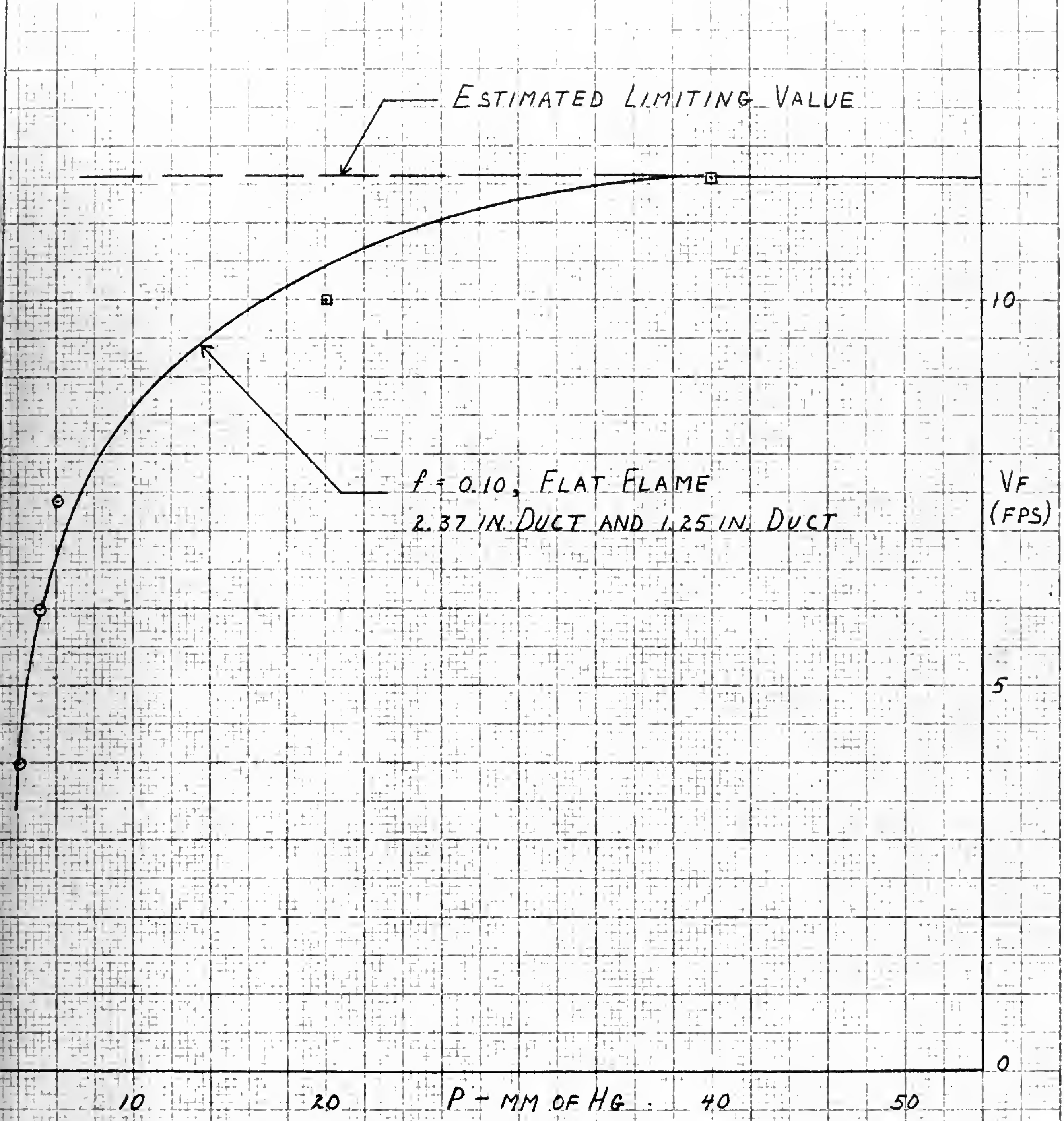

FIG. 12

VARIATION OF C_2H_2-O_2
FLAME SPEED
WITH PRESSURE

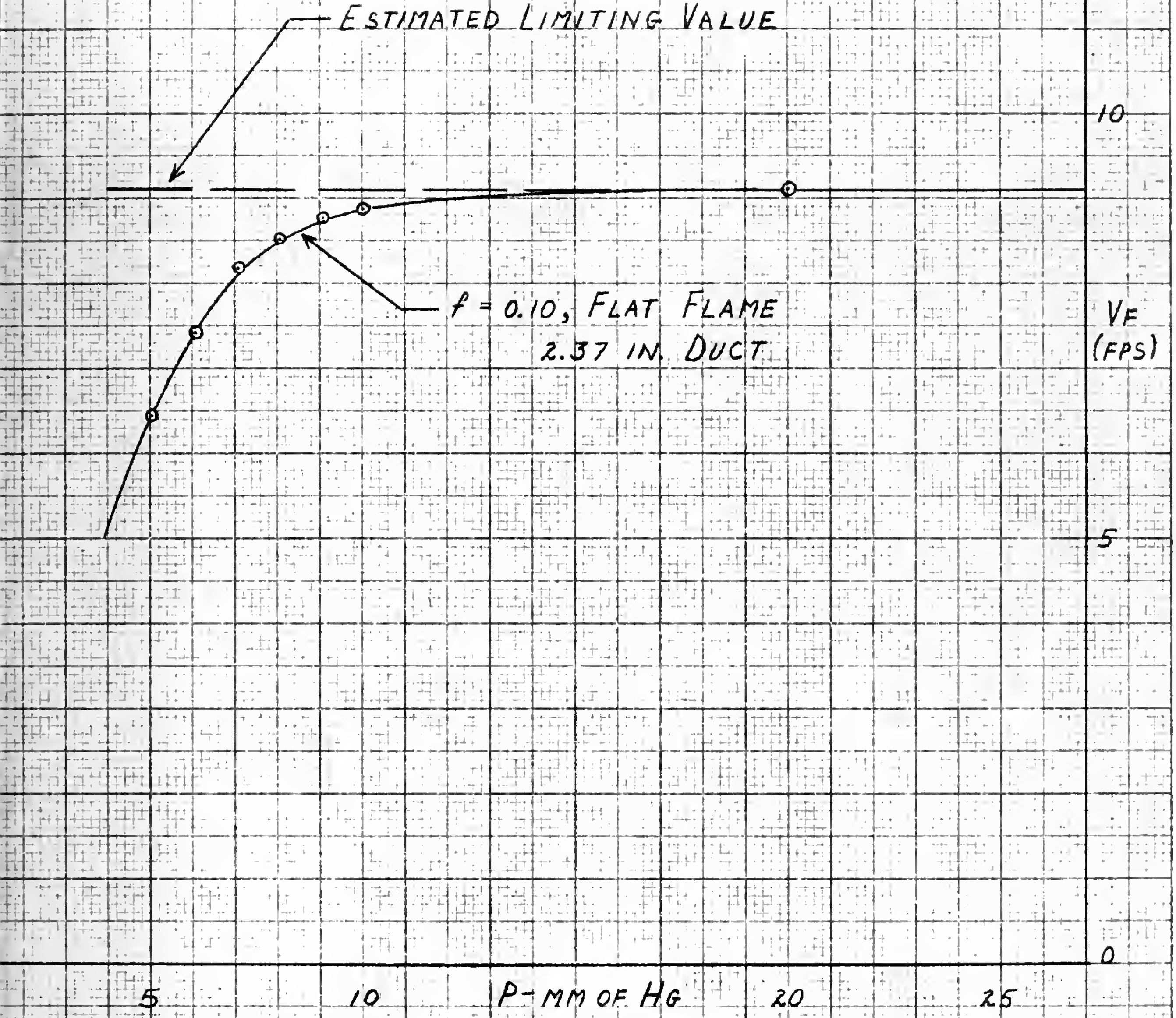

FIG. 13

VARIATION OF $C_3H_8-O_2$
FLAME SPEED
WITH PRESSURE

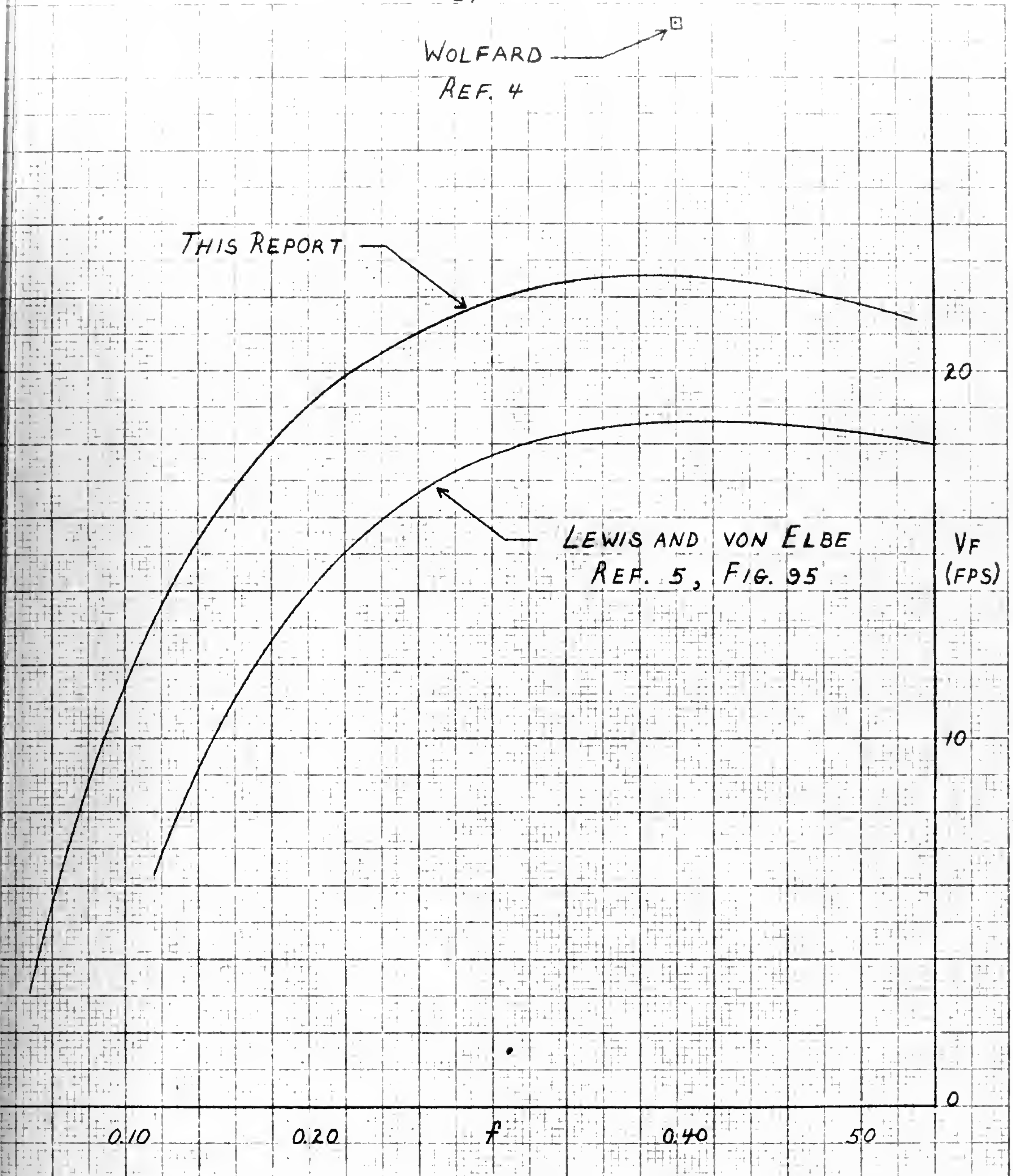

FIG. 14

COMPARISON OF C_2H_2-O_2 LIMITING CURVE WITH ATMOSPHERIC PRESSURE DATA

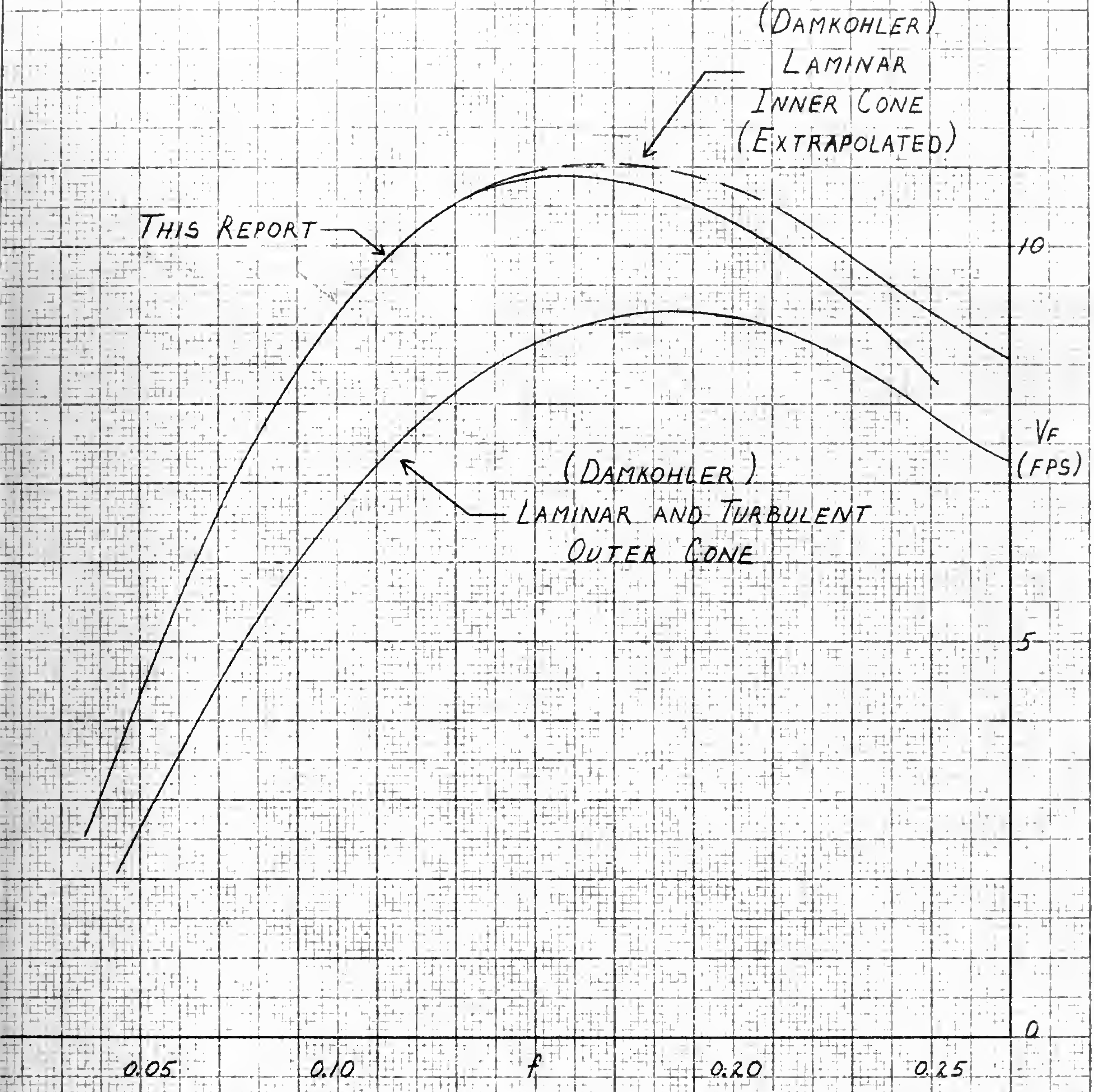

FIG. 15

COMPARSION OF C_3H_8-O_2 LIMITING CURVE WITH ATMOSPHERIC PRESSURE DATA

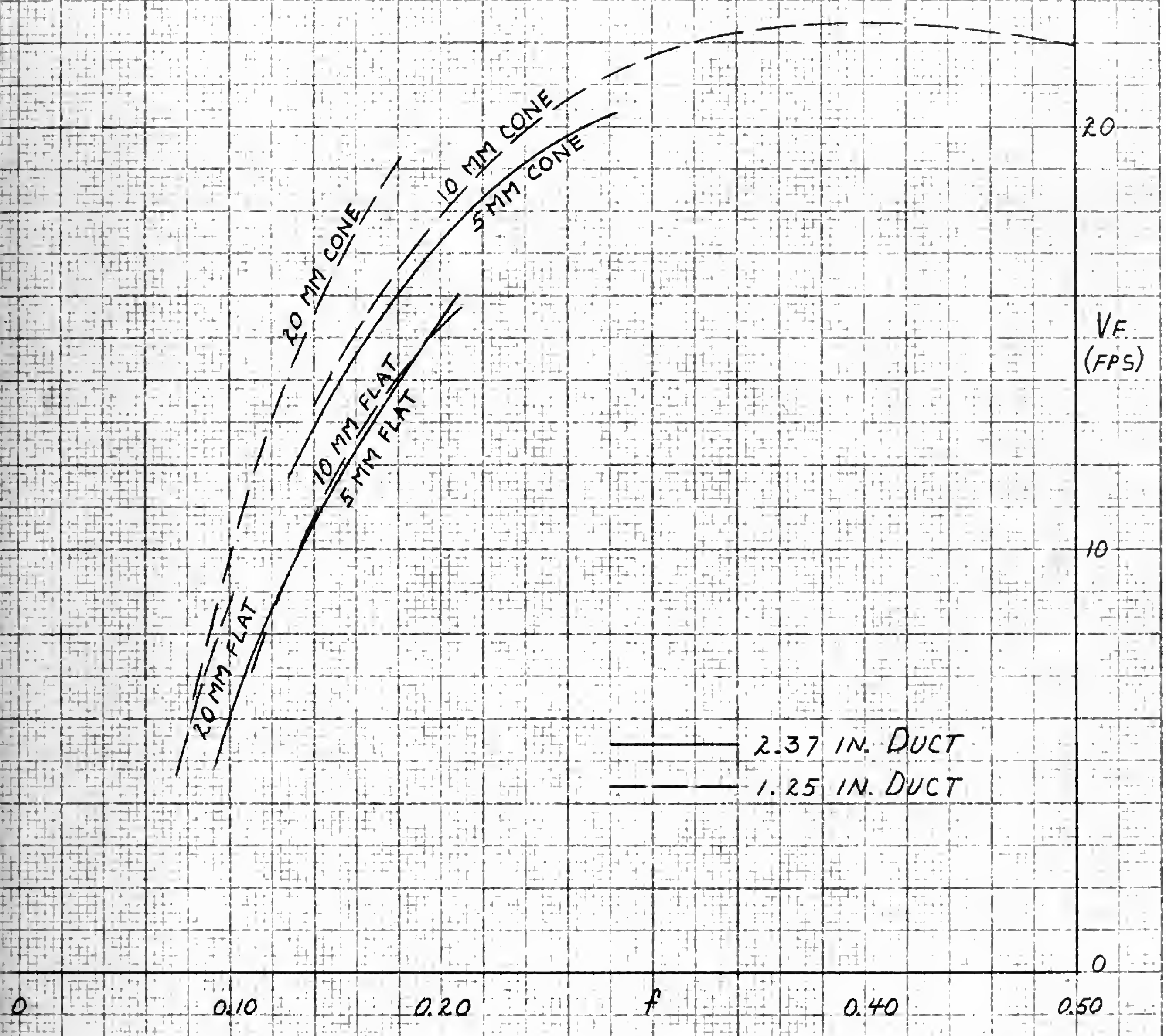

FIG. 16

EFFECT OF FLAME GEOMETRY ON C_2H_2-O_2 FLAME SPEED

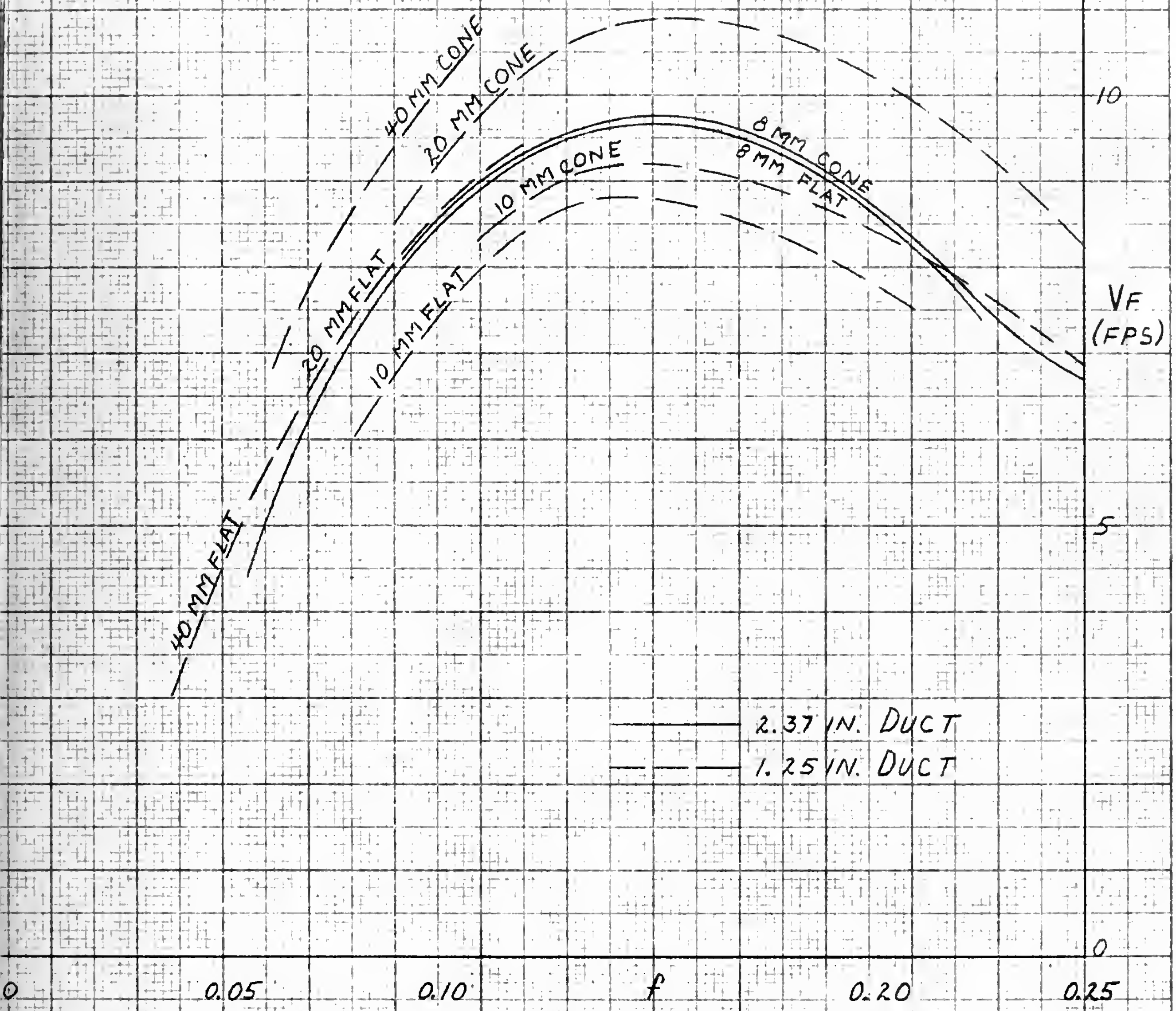

FIG. 17

EFFECT OF FLAME GEOMETRY ON $C_3H_8-O_2$ FLAME SPEED

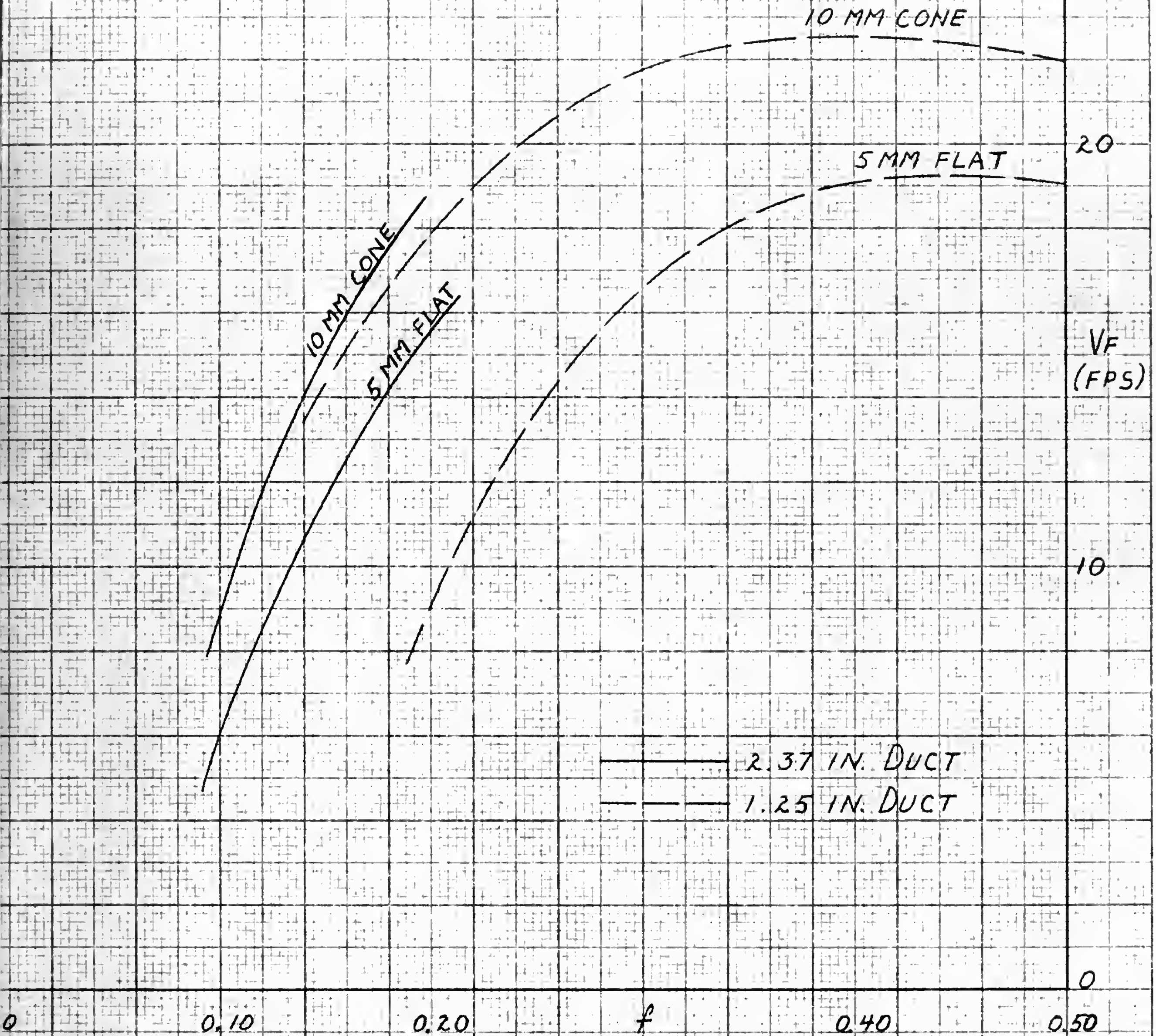

FIG. 18

EFFECT OF BURNER INLET DUCT DIAMETER ON $C_2H_2 - O_2$ FLAME SPEED

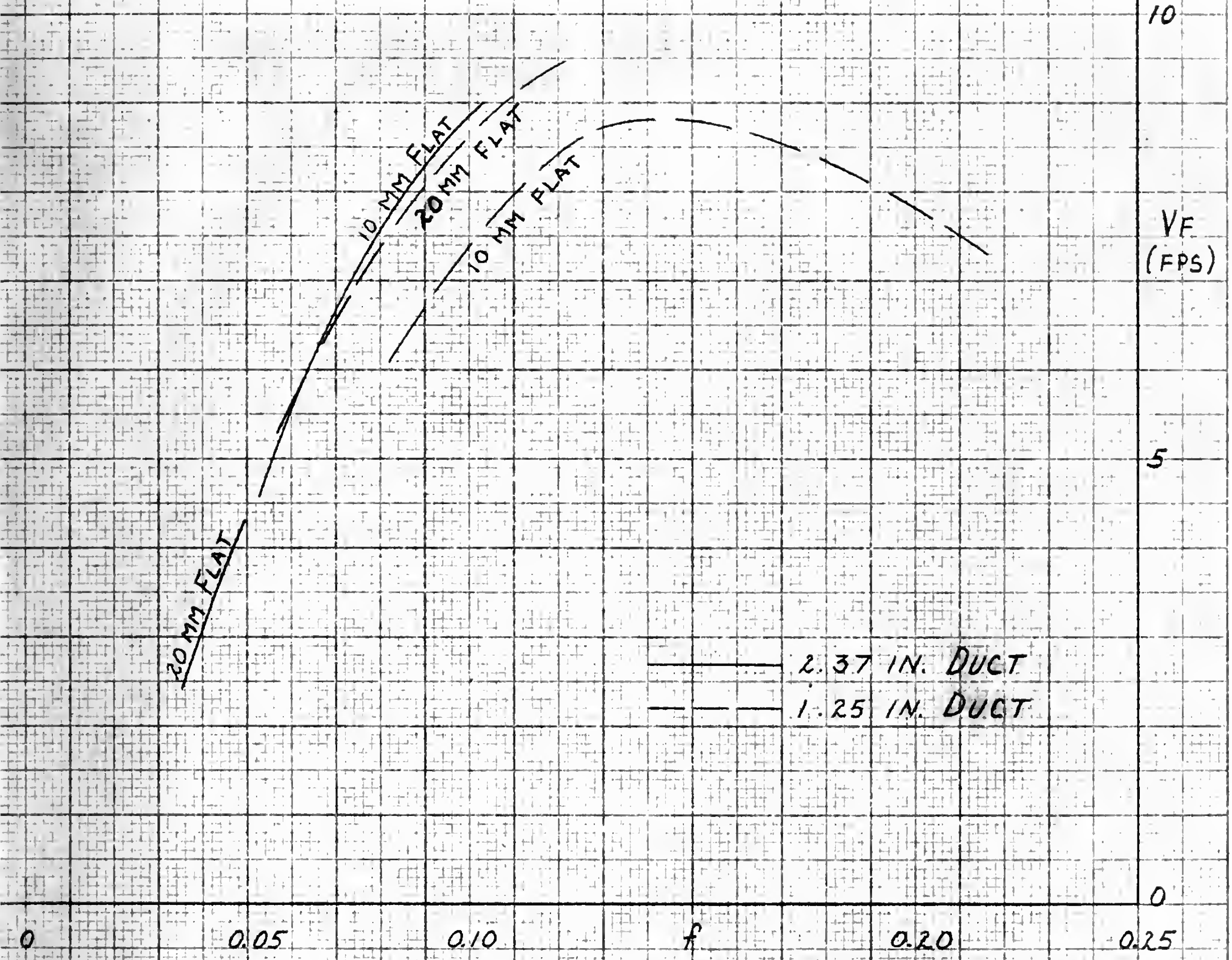

FIG. 19

EFFECT OF BURNER INLET DUCT DIAMETER ON C_3H_8-O_2 FLAME SPEED

Thesis 17324
E58 Eriksen
Investigation of flame velocities at low pressures.